NETWORK DESIGN FOR SURVIVABLE MILITARY SATELLITE COMMUNICATION.

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Monterey, California

THESIS

NETWORK DESIGN FOR SURVIVABLE
MILITARY SATELLITE COMMUNICATION

by

Kusnadi Djati Juwono

March 1978

Thesis Advisor: G. Howard

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Network Design for Survivable Military Satellite Communication

5. TYPE OF REPORT & PERIOD COVERED
Master's Thesis;
March 1978

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Kusnadi Djati Jowono

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

12. REPORT DATE
March 1978

13. NUMBER OF PAGES
54

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Communication Network
Survivability Criterion
Satellite ground terminals
Communication Satellite

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(20. ABSTRACT Continued)

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Network Design for Survivable
Military Satellite Communication

by

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Captain, Indonesian Air Force
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
March 1978

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENT

The author wishes to express his appreciation to Professor G.T. Howard for the invaluable aid and advice which he has offered during the preparation of this thesis and to Professor G.F. Lindsay for his suggestions and corrections of the final manuscript.

I. INTRODUCTION

A. BACKGROUND

In July 1977 Indonesia's second domestic satellite was launched. That was part of the Government's major program in developing a new communication system. The main goal of establishing a new communication system is to provide a good and reliable public communication system all over the country. Since Indonesia consists of many islands, stretching over 5000 km, then the system that will provide low cost, reliable communication spanning thousands of kilometers of land and water is a satellite system. Under this kind of system, geographical conditions of the country will become a less important factor.

The Indonesian Armed Forces, as an organization having responsibilities of national defense and security, also needs a reliable communication system that is able to support the Nationwide Command and Control System. The existing high frequency (H-F) military communication system does not provide adequate support to the Armed Forces to carry out the mission due to the limited performance of the system. The H-F communication system is highly dependent on the meteorological conditions. In a tropical country, where weather phenomena are unstable, the H-F transmission is unreliable. It is not unusual to have an indirect transmission of messages from a particular military installation to the Headquarters

or vice versa. But the most serious disadvantage of the existing H-F communication system is the poor security due to the nondirectivity of propagation.

To improve the existing communication system, the military sees a possibility to use a satellite as the media of its communication. The satellite system is considered to be critical to national defense and security. It has some technical characteristics that are ideally suited for military purposes, such as high quality secure voice, high speed data transfer, and real time accurate data processing, Moreover, the availability of portable satellite terminals yields three favorable aspects: less vulnerability, more flexibility and greater coverage. Thus, whenever emergencies dictate, access to remote and hostile areas not served by the government system can be quickly established using transportable ground terminals.

Considering the above facts, and since the need for improvement of the existing communication system is real, a new military satellite communication system must be properly defined and developed.

B. MILITARY REQUIREMENTS CONSIDERATIONS

A military communication system is supposed to operate under all environmental conditions or potential threats. It must be capable of directing and monitoring peacetime operations, providing tactical warning, directing wartime decisions and monitoring the execution of the decisions.

Due to these specific functions that must be fulfilled, military communication systems must satisfy some additional requirements beyond those for public systems.

La Vean [1] analyzes some requirements imposed on the U.S. Defense Satellite Communication System (DSCS). These distinct requirements usually refer to some features that must be fulfilled by a military communication system, and it generally can be stated that they will drive up the system's cost.

Since satellite communication for the Indonesian Armed Forces is in its early stage, only three of the many military requirements will be considered. They are:

1. Positive operational control
2. Survivability
3. Security.

Positive operational control means that the system must be under military command and control at all times. Military links are so vital that only military facilities can be used to establish and maintain them.

The survivability of a military communication network can be interpreted as electronic and physical survivability. Electronic survivability is the ability of the networks to survive from enemy's electronic countermeasures. This problem is technical in nature and it is concerned with the use of sophisticated electronic devices. Physical survivability of the networks is the ability to survive after an enemy attack or sabotage. It is a function of the probability of

survival of the terminals and the links. To enhance the survivability of the networks one might increase the probability of survival of the terminals or the links, or one might increase the number of links between any pair of terminals without increasing the probability of survival of each link. One may also change the topology of the network or use some combination of these techniques. In this thesis only physical survivability of the networks will be considered.

A reasonable measure of the survivability of a network is the minimum number of links "m" that must be destroyed before a particular node cannot communicate with any other node. In other words, there must be at least "m" disjoint paths between any pair of nodes. The number "m" is usually called the link redundancy.

The security requirement is more technical in nature, concerned with coding and decoding the messages, digitization of voice signals, type of modulation and carrier frequency used. It is also related to the communication media involved. It was already noted in the previous section that the existing H-F communication system has a poor security and steps must be taken to improve it.

C. SYSTEM'S ALTERNATIVES

There are three system's alternatives that can be adopted as the new military communication system. They have different capabilities of satisfying the requirements discussed in the

previous section and they also differ significantly in investment cost. These three systems alternatives are:

1. Complete dependence on the government system,
2. Full military system, and
3. Quasi-military system.

In the first system's alternative, the military installations get access from the government's ground terminals and use the links as an ordinary public subscriber. Notice that the government system is designed for public use and it is administered and operated by the Directorate of Post and Telecommunication. Thus they focus their attention only to public and governmental needs. Hence it is clear that none of the military requirements are satisfied by this type of system. To adopt this system as a military communication network will be an improper choice.

The second system alternative requires building a separate satellite communication system strictly for military purposes. This is the best communication system the Armed Forces might have, but it requires tremendous investment cost. The cost consideration prohibits the Armed Forces from choosing this sytem.

In the third system alternative, some components of the system are operated by the military and the others are under the government's control. To select which components of the system will be under military control, notice that the satellite is less vulnerable than the ground components of the system. Moreover, the cost of the satellite and the

cost of putting it into an orbit contribute the largest part of the construction cost of a satellite communication system. Thus the best way to adopt this alternative will be to use some channels from the government's satellite and to build separate satellite ground terminals and terrestrial networks strictly for military purposes. Under this kind of system, the required investment cost will be reduced significantly and the military will have a full command and control over the more vulnerable components of the system, i.e., the terrestrial network. A special protection to increase the invulnerability of the terrestrial network can be provided by the Armed Forces, once it is under their control. Hence, considering the trade-off between the cost saving incurred and the degree of control over the system, to adopt this system as the new military communication system will be an optimal choice for the Armed Forces.

Once the satellite is available, the new military communication system might consist of satellite links only. In this case there must be a ground terminal in every military installation. Considering the number of military installations included in the communication network, this kind of system will require a large investment cost, hence it will not be considered.

Another approach for the new military communication system is to build a satellite ground terminal for several military installations, and then construct the terrestrial network connecting these military installations to the

satellite terminal. This approach will reduce the investment cost required since it is not required to build a satellite ground terminal in every military installation. In this thesis, this type of system will be considered as the new communication system of the Indonesian Armed Forces.

To enhance the security of the system, we will suggest replacing the existing H-F links with microwave links having a high directivity of propagation. The microwave links that are commonly used today for terrestrial communication systems fall into two main categories, namely, line-of-sight (LOS) and tropospheric-scatter links. The tropospheric-scatter has some advantages over LOS systems when the intervening terrain is accessible only with difficulty or when sea crossings are involved, but its construction, operating and maintenance costs for the same number of channels and same distances are far more expensive than LOS systems [2]. Since the tropospheric-scatter system does not require remote repeater stations, then the survivability of tropospheric-scatter links is higher than LOS links, however the cost incurred is significantly large. Provided that the satellite links are available, then the advantages of the tropospheric-scatter system stated above will diminish. Thus, the LOS link will be used in the terrestrial network of the new military communication system and special efforts will be given to improve its survivability.

In this thesis, an heuristic solution method for designing a new military communication network consisting of satellite

and terrestrial LOS links is presented with emphasis on the survivability of the terrestrial network. The survivability criterion imposed on the network will be defined in the next chapter.

II. PROBLEM STATEMENT

To understand the problem, it is necessary to understand the communication procedure in the Indonesian Armed Forces.

Indonesia is divided into four Defense Area Commands (DAC). In each DAC there are several Military Region Commands (MRC) of the Army, Navy and Air Force. The locations of DAC and MRC Headquarters are shown in Figure 1. DAC coordinates the joint operational activities of the Armed Forces in its area. Thus from each MRC Headquarters there must be a communication link to DAC Headquarters. Also from DAC Headquarters to the Department of Defense (DOD) in Jakarta as the highest operational command in the Armed Forces. These links are used to support the command and control activities of the Armed Forces.

Moreover, each MRC Headquarters should have a link to it's respective Service Headquarters in Jakarta. These links provide support to the administrative activities of the Armed Forces. The two kinds of links and the communication procedure are shown on Figure 2.

The existence of two kinds of links, operational and administrative does not imply that there should be two communication systems. Those links only show the hierarchal procedures of operational and administrative activities in the Indonesian Armed Forces and both can use the same system.

Notice that most of the communication links are going to Jakarta. This is obvious since the Headquarters of the

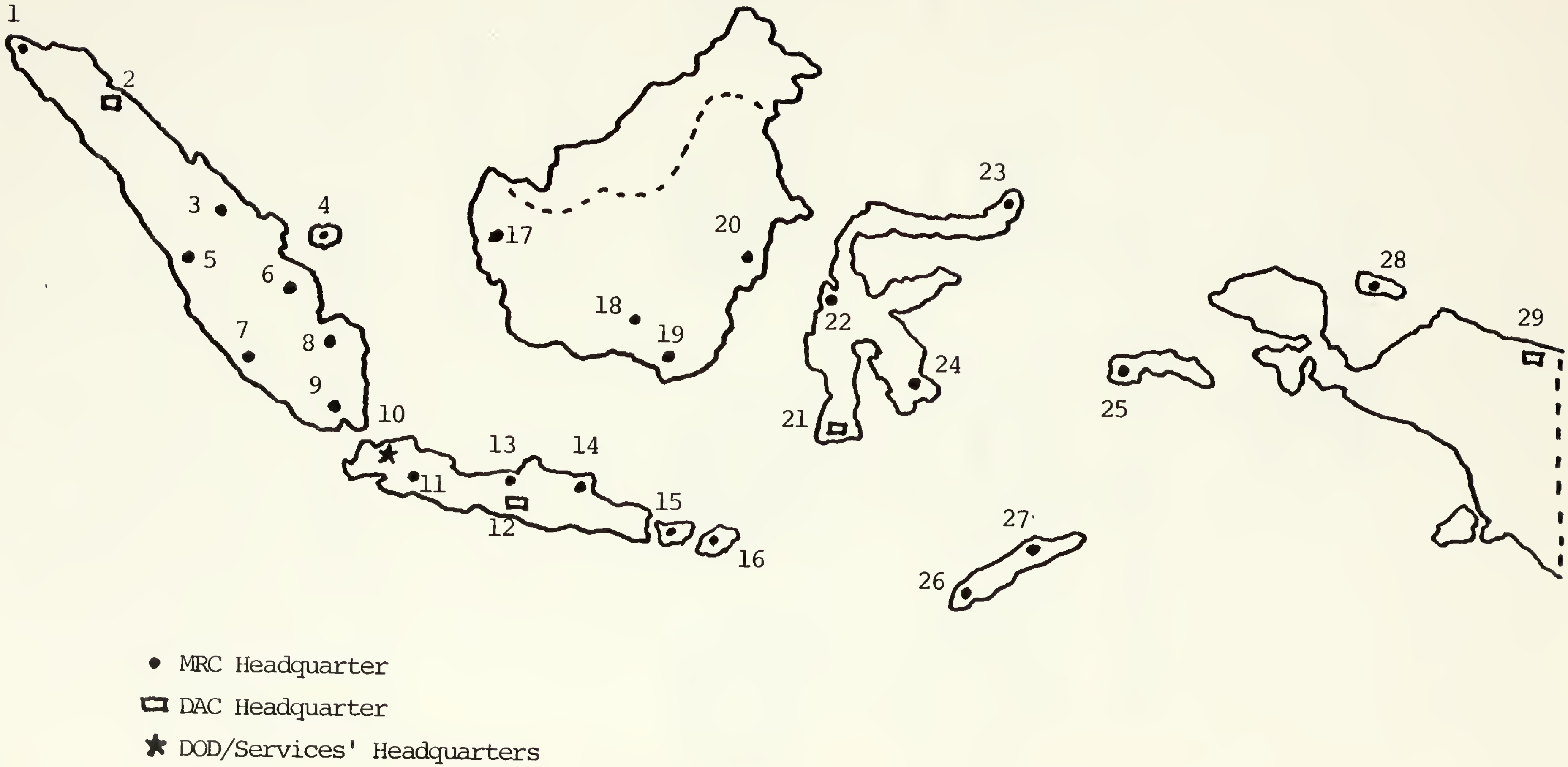

FIGURE 1. Locations of DAC and MRC Headquarters

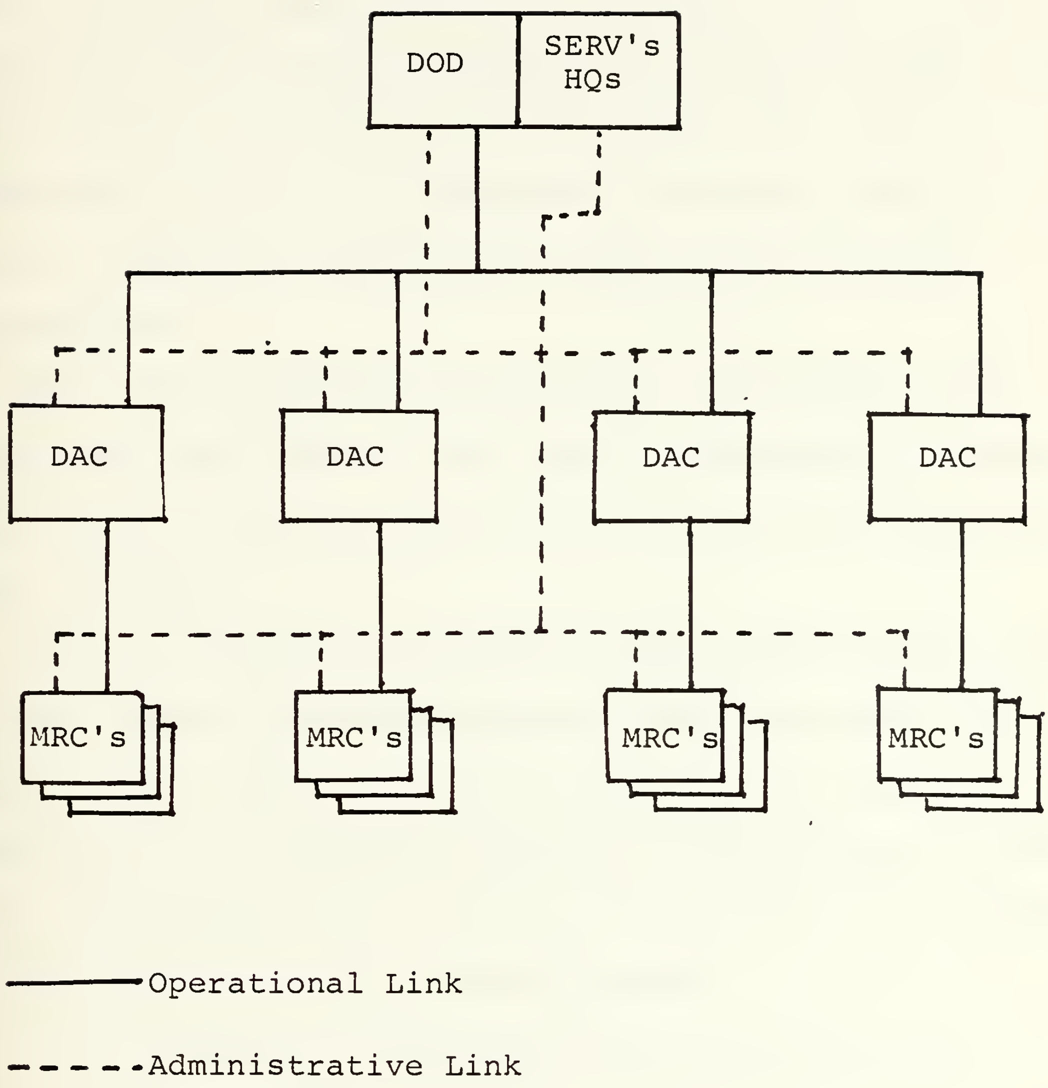

FIGURE 2. Communication Procedure

highest commands in the Armed Forces are located in Jakarta. In practice, it is also desirable for the DAC Headquarters to be interconnected. These links might be used for a direct exchange of information concerning threat, force status and other ongoing activities. The connections between MRC Headquarters will not be emphasized since there is no necessity to do so. In the case of emergency, they will always be able to communicate to each other via DAC Headquarters.

From the hierarchal communication procedure in the Indonesian Armed Forces, the required connections between Headquarters can be represented by an incidence matrix as shown in Table 1.

The survivability criterion imposed requires the network to have connections satisfying the incidence matrix in Table 1, each with at least "m" node-disjoint paths. Depending on the distance between the Headquarters, these paths might consist of satellite, terrestrial or a combination of both types of links. Assuming that:

1. The satellite terminals and links are highly invulnerable,
2. The expected threat is from air or ground attack using conventional armament,

then the problem of survivability will be focused on the terrestrial links only. Since the MRC or DAC Headquarters that cannot communicate directly with DOD or the Service Headquarters must be connected to a satellite terminal, the

TABLE 1. The Required Connections Between Headquarters

HEADQUARTERS

HEADQUARTERS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1		1								1																			
2			1	1	1	1	1	1	1	1																			
3										1																			
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redundancy "m" will be applied to the links connecting the MRC or DAC Headquarter to the satellite terminal. The value of "m" assigned to each Headquarters might be different. To show this difference, the survivability criterion of the military communication system will be written as m_i - the minimum number of node-disjoint paths from the i^{th} Headquarters to some satellite terminal; i = 1, 2, ... 29.

Thus, given some information about the locations of the Headquarters, the required connection between Headquarters and the survivability criterion for the networks and knowing that the link redundancy will increase the system's construction cost, we define the problem as to find a method for constructing a low cost military communication network with a least m_i node-disjoint paths from each Headquarters to some satellite terminal.

The method must be able to

1. find the required number of satellite terminals,
2. find the best location (in terms of cost) for the satellite terminals,
3. select which nodes are connected to which satellite terminal (to cluster the nodes),
4. find a low cost configuration of the terrestrial network satisfying the given link redundancy m_i.

III. THE MODEL

Given the location of military Headquarters in Figure 1, the incidence matrix shown in Table 1 and the values of m_i for all Headquarters, the communication network can be modeled as an undirected graph with Headquarters corresponding to nodes and links corresponding to branches.

To generalize the problem assume that we have a set of nodes $N = \{N_1, N_2, \ldots, N_n\}$ and a required incidence matrix. We are also given a set of possible locations for the satellite ground terminals $T = \{T_1, T_2, \ldots, T_t\}$. This set T must satisfy two basic requirements:

1. The location of satellite ground terminal must guarantee a full support to the terminal to perform it's technical functions.
2. It must have full protection against physical attack.

Let us define the following:

N : the set of all nodes

N_i : the i^{th} node

n_i : the weight attached to N_i, representing the number of channels that must be connected to N_i to handle the messages that originate or terminate at N_i

g_j : the weight attached to satellite terminal T_j, representing the channel-capacity of T_j

ℓ_{ik} : a link connecting N_i and N_k

p_{ik} : the capacity of link ℓ_{ik} in number of channels

d_i : the degree of N_i, that is, the number of links incident with N_i.

The link redundancy m_i for each node N_i means that the degree of each N_i is at least m_i. The degree of the nodes will have an effect on the number of links in the network, which in turn, will affect the cost of establishing the links. Thus, when constructing a network with link redundancy m_i for each node N_i, we will assume the degree of each node d_i is exactly equal to m_i since this configuration gives the minimum number of links.

Hence if ST is a set of s satellite terminals, NM is a set of n nodes having microwave terminals and SN if the union of ST and NM, then given m_i for all $N_i \in NM$, the overall terrestrial communication network can be modelled as an undirected graph with an n by n+s incidence matrix $X = \{x_{ib}\}$, where i is the subscript of $N_i \in N_M$ and b is the subscript of either $N_i \in NM$ or $T_j \in ST$ and

$$x_{ib} = \begin{cases} 1 & \text{if there is a link } \ell_{ib} \text{ between } N_i \in NM \text{ and } N_k \in NM \text{ or } T_j \in ST, \; i \neq k \\ 0 & \text{otherwise .} \end{cases} \tag{1}$$

$$\sum_b x_{ib} = m_i \quad \text{for all } b \text{ subscript of } N_k \in NM \text{ and } T_j \in ST . \tag{2}$$

Since each node must be connected to a satellite terminal either directly or via any other node, then

$$\sum_i n_i \leq g_j \quad \text{for all } N_i \text{ connected to } T_j . \tag{3}$$

The total construction cost of the network can be written as

$$TC = \sum_{T_j \varepsilon ST} G_j + \sum_{N_i \varepsilon NM} I_i + \sum_i \sum_b x_{ib} \cdot C_{ib} , \tag{4}$$

where

G_j : the cost of establishing j^{th} satellite terminal (T_j) ,

I_i : the cost of establishing microwave terminal at N_i , and

C_{ib} : the cost of establishing link ℓ_{ib} .

The costs G_j and I_i depend on the size of the terminals. Once determined, then throughout the process of designing the network and computing the construction cost, G_j will be constant. I_i, on the other hand, will be related to the topology of the network as explained in section IV.C.

The cost C_{ib} depends on the length of ℓ_{ib} and also on the link capacity p_{ib}. The exact dependency of cost on the length and capacity of the link has not yet been formulated. In most studies, the cost of establishing a link is expressed as a function of one of these variables. In this model, since length is fixed, the cost of establishing a link really depends only on capacity (one variable). It is assumed that this cost is a linear function of link's capacity. Then if c_{ib} is the cost of establishing link ℓ_{ib} for one unit capacity, the link's cost function can be written as

$$C_{ib} = c_{ib} \cdot p_{ib} \tag{5}$$

Thus, in terms of the mathematical expressions defined, the model can be written as:

minimize	TC	
subject to	$\sum_b x_{ib} = m_i$	for all $N_i \in NM$
and	$\sum_i n_i \leq g_j$	for all N_i connected either directly or via any other node to T_j .

IV. SOLUTION METHOD

To solve the problem, one might start with predetermined locations of satellite terminals and then construct the terrestrial network. The difficulties with this method are that the required number of satellite terminals is unknown and also that the given fixed locations will not guarantee the least expensive connection to the nodes.

Another way to solve the problem is, first, to partition the network, that is, divide the nodes into several disjoint-subsets. By doing this, we will have to identify approximate locations of the satellite terminals. Since in each subset there will be a separate subnetwork, independent of the others, the design problem of each subnetwork will also be solved separately. However these problems are similar, thus the solution method can be developed from one subnetwork. The same solution method must also be able to solve the problem in each other subset. When the problem in each subset has been solved, it means that the overall terrestrial network has also been determined.

A. NETWORK PARTITION

There are two approaches that can be used to partition the network. They are:

1. to use the organizational requirement,
2. to use the geographical conditions of the area.

Under the first method, since each MRC Headquarters must be connected to some DAC Headquarters, the communication network will be partitioned according to the area of each DAC. In each DAC we would then solve the design problem. This method is good when the line of sight (LOS) link between any pair of MRC Headquarters in each DAC is possible.

The second method considers the fact that a LOS link is not always possible due to geographical conditions of the area. For example, in Figure 1, the MRC Headquarters are separated from each other by different terrain such that LOS links sometimes are impossible. Thus the method is to divide the nodes into several disjoint-subsets such that these subsets can not communicate with each other using only LOS links.

Using the second method for partitioning the communication network of the Indonesian Armed Forces, let us define

R_u: a set of nodes that can not communicate using LOS links to anything outside the set; $u = 1, 2, \ldots r$, where r is the total number of the sets.

It is obvious that

$$R_u \cap R_v = \phi \quad \text{if} \quad u \neq v ,$$

and

$$\bigcup_{u=1}^{u=r} R_u = N .$$

Since the nodes in each set R_u cannot communicate to any other nodes outside the set using LOS links, then the communication between sets must be provided using satellite links. In other words, to satisfy the required connection as shown in Table 1, then in each set R_u there must be at least one satellite terminal.

The exact number of satellite terminals in each set R_u basically depends on the total demand of the nodes in the set and also on the size of satellite terminal used. We consider three sizes of satellite terminals. Each size is associated with the number of channels it is able to handle. Thus, depending on the total demand of nodes in Ru and on the sizes of the satellite terminals chosen, we might have more than one satellite terminal in that particular R_u . Then the total number of satellite terminals in the overall network will be the sum of the number of satellite terminals in each R_u , once these have been determined.

The location of satellite terminals must be chosen from the set T such that the total realization cost of the network is a minimum. For example, if it was decided to have two satellite terminals in a particular R_u , the first choice might be given to the nodes having the largest demands if they are also elements of set T . If they are not, we would pick two elements of set T which are nearest to them. If the demands do not differ significantly, then for each possible combination of two elements of set T ,

we suggest solving the problem, and then to adopt the combination having the least realization cost. The number of combinations might be reduced significantly using careful military and technical judgments.

In the case of having, for example, k satellite terminals $(k > 1)$ then each satellite terminal and the nodes connected to it will form a separate subnetwork. The design problem must be solved separately for each subnetwork. In doing this we must first find a way to cluster the nodes, that is to choose which nodes are to be connected to which satellite terminal.

We do not consider interconnecting the clusters via the terrestrial network, but it might be wise to do so since this would allow one satellite terminal to carry the emergency traffic if the other is out of service.

B. CLUSTERING THE NODES

The method of clustering the nodes is generally dictated by the dispersion of the nodes in R_u .

There are two basic methods that we may use. They are:

1. Minimal spanning tree: Construct a minimal spanning tree connecting all nodes, then eliminate (z-1) longest links, where "z" is the desired number of clusters. For example, we have 11 nodes and the minimal spanning tree connecting all nodes is given in Figure 3. Suppose it was decided to have two

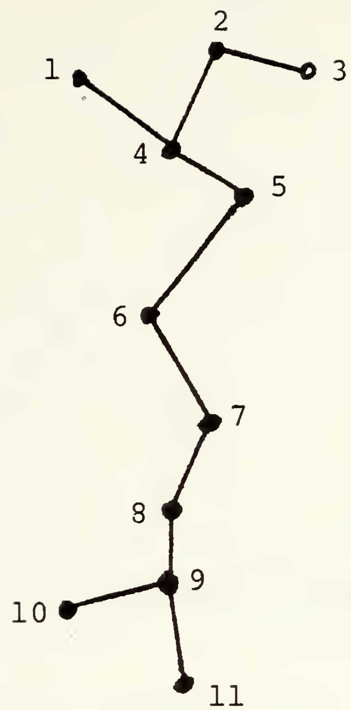


FIG 3. MINIMAL SPANNING TREE

satellite terminals, T_1 and T_2. We would consider locating them at N_4 and N_9 respectively, and then eliminate the longest link, that is ℓ_{56}.

2. Nearest-Neighbor: the nodes will be connected to the satellite terminal with the lowest cost of connection. We can do this simply by comparing the cost of connecting a node to different satellite terminals. In the example in Figure 4 (next page), we have 11 nodes. If there must also be two satellite terminals T_1 and T_2, we consider locating them

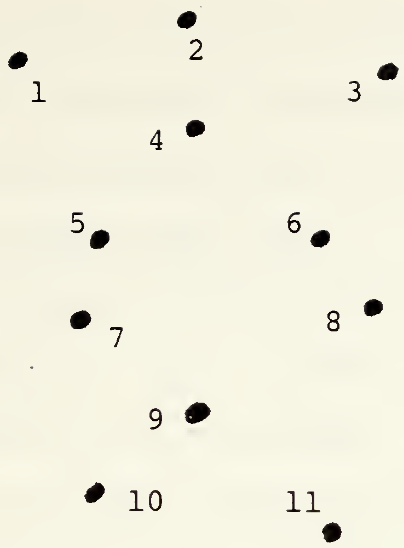


FIGURE 4. THE NEAREST NEIGHBOR

at N_4 and N_9 respectively. Then by comparing the cost of connecting each node to either T_1 or T_2, we might have, for example $\{N_1, N_2, N_3, N_5\}$ in one cluster with T_1 and $\{N_7, N_8, N_{10}, N_{11}\}$ in another with T_2.

To decide which method will be used in a particular problem, a careful judgment is needed. For example, consider the nodes shown in Figure 3. If one uses the Nearest-Neighbor Method to cluster these nodes, one might include N_6 in a cluster together with T_1, N_1, N_2, N_3, and N_5 since the distance from T_1 to N_6 is shorter than the distance from N_6 to T_2. To connect N_6 to T_1 through N_5, however, will be more expensive than to connect N_6 to T_2 through N_7, since the distance from N_5 to N_6 is longer than the distance from N_6 to N_7.

In Figure 4, the satellite terminals are located more centrally relative to the locations of the nodes. If one uses the Minimal Spanning Tree method, one might eliminate ℓ_{78}, then include either N_7 or N_8 in a cluster together with T_1. However, it is in fact better to connect both of them directly to T_2. Thus in this case, the Nearest Neighbor method is more suitable.

The most important things that must be emphasized in clustering the nodes are that the clusters must not overlap, that is, their intersections are void and the capacity constraint of each satellite terminal as expressed by formula (3) must be preserved.

Notice that each cluster will have exactly one satellite terminal. Since the solution method for the design problem will be developed in one cluster, then to simplify the notation, through the rest of this thesis the subscript "j" in T_j will be dropped.

The capacity constraint of formula (3) is not fully applicable in the cluster with the node representing Jakarta in it. The satellite terminal in this cluster is used to provide connections between Jakarta and the other nodes outside the cluster. The communication inside the cluster will be provided by LOS links. Thus if Jakarta has weight n_a and some portion of this weight, say n_a^*, is for the communication inside the cluster, then the capacity of the satellite terminal in this cluster must satisfy

$$(n_a - n_a^*) \leq g_a \quad . \tag{6}$$

C. COST STRUCTURE

We already stated that the design problem for each subnetwork will be solved separately, then the construction cost of the overall network will be based on the cost structure of each subnetwork. In the j^{th} cluster containing one satellite terminal T and a set NM of nodes having microwave terminals, the construction cost is

$$TC_j = G + \sum_{N_i \varepsilon NM} I_i + \sum_{\substack{N_i \varepsilon NM \\ N_k \varepsilon NM \text{ or } T}} x_{ik} \cdot C_{ik} \qquad (7)$$

The link's cost C_{ik} can be computed using formula (5).

To compute the link capacity p_{ik} and also to determine the cost I_i we use the following consideration. The demand n_i of each node is the number of channels required for conducting the operational and administrative activities. In any case, this number must be preserved. Thus if there are m_i disjoint paths from N_i to T, then in each path, the demand n_i must be satisfied. This method will have the effect that in the worst case in which the network still functions, that is, all but one path from N_i is destroyed, there are still n_i channels available for N_i. The demand of any other nodes on these paths must be adjusted such that they are also able to handle n_i. In other words, we define p_{ik} as the minimum required number of channels in the link ℓ_{ik} and the adjusted demand n_i' of node N_i as the minimum number of channels that must be handled by

the terminal at N_i . The quantity p_{ik} determines the cost C_{ik} and n_i' determines the size of the terminal at N_i and its acquisition cost.

As an illustrative example of computing p_{ik} and n_i' , consider the network in Figure 5. Suppose ℓ_{3T} was

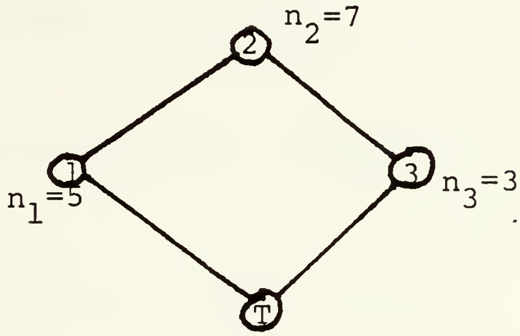


FIGURE 5. ILLUSTRATIVE EXAMPLE FOR COMPUTING p_{ik} and n_i'

destroyed, then N_3 must communicate to T via N_2 and N_1 and N_2 must communicate to T via N_1 . The capacity of the links constructing the path from N_3 to T and the capacity of the terminals on this path must reflect this consideration. The terminal at N_1 must be able to handle the messages going to and coming from N_1, N_2 and N_3 simultaneously. Likewise link ℓ_{1T} must be capable of handling all the traffic for nodes N_1, N_2 and N_3 . The same situation will arise for N_3 and ℓ_{3T} if we suppose ℓ_{1T} is destroyed.

By considering all possible cases of link destruction in which the network still functions, the link capacities and adjusted demands for the network in Figure 5 will be

$$n_1' = \max\{n_1, (n_1+n_2), (n_1+n_2+n_3)\} = 15 ,$$

$$n_2' = \max\{n_2, (n_1+n_2), (n_2+n_3)\} = 12 ,$$

$$n_3' = \max\{n_3, (n_3+n_2), (n_3+n_2+n_1)\} = 15 ,$$

$$\ell_{1T} = \max\{n_1, (n_1+n_2), (n_1+n_2+n_3)\} = n_1' = 15 ,$$

$$\ell_{12} = \max\{n_1, (n_2+n_3)\} = 10 ,$$

$$\ell_{23} = \max\{(n_1+n_2), n_3\} = 12 ,$$

and

$$\ell_{3T} = \max\{n_3, (n_3+n_2), (n_3+n_2+n_1)\} = n_3' = 15 .$$

It is important to note that the capacity of a link incident to the satellite terminal is always equal to the adjusted demand of the node adjacent to it, or

$$\ell_{iT} = n_i' . \qquad (8)$$

Once the adjusted demand of each node is computed, the cost I_i can be determined, and when the link capacities have been found, the cost matrix $C = \{c_{ib}\}$ can be used to determine the construction cost of the links in the j^{th} cluster using formulas (5) and (7).

The total construction cost of the overall communication network expressed by formula (4) then can be determined as the sum of all construction costs of the subnetworks, i.e.

$$TC = \sum_j TC_j \quad . \tag{9}$$

D. THE ALGORITHM

There exist some algorithms for constructing a low-cost survivable network. The algorithm proposed by Hakimi [3] can be modified for constructing a least vulnerable network under least-cost constraint when the cost of links is not uniform. Steiglitz et al. [4] proposed an heuristic approach for finding a near optimal configuration using a random starting routine and an optimizing routine. The cost of the link in their model is only a function of distance, thus independent of the capacity of the link. Due to the differences in the cost structure of the network, we will use a different algorithm.

The algorithm used for finding the least-cost configuration of each network is heuristic, and it begins with a

nonfeasible solution in which all nodes are connected directly to the satellite terminal with m_i links, and modifies it until a feasible solution is obtained. We then attempt to reduce the construction cost by employing a "link-exchange" procedure.

By a feasible solution we mean a configuration of a subnetwork having the following properties:

1. All nodes are connected to the satellite terminal either directly or via other nodes,
2. The degree requirement of each node is satisfied, and
3. There are no parallel branches between any pairs of nodes.

Let us define

NM : the set of nodes in j^{th} cluster having microwave terminals,

IN : The set of nonfeasible nodes, that is, nodes having more than one link connected directly to T ,

$\overline{IN}$: The set of feasible nodes, that is, nodes having at most one link connected to T , while the remaining links are connected so some different nodes,

L : The set of existing links.

It is clear that $IN \cap \overline{IN} = 0$ and $IN \cup \overline{IN} = NM$.

The algorithm is started by assigning all nodes to the set IN so that each node is connected directly to T by

m_i parallel links. At each step, at least one element of IN is transferred to $\overline{\text{IN}}$. This transfer is made possible by successively inserting a new link connecting the node to be transferred, say N_i, to different nodes and at the same time deleting the link from N_i to T and the link from T to the node being considered for connection to N_i. We stop considering this node when there is only one link remaining from N_i to T. In this case N_i is not an element of IN anymore. Each time we consider inserting a new link from N_i to any other node, say N_k, and at the same time deleting links from N_i to T and from N_k to T, we compute the cost of the configuration. We pick the one having minimum cost. For all nodes connected to N_i at the end of this step, each must have provided the minimum cost among all nodes considered. Then, we update IN, $\overline{\text{IN}}$ and L by transferring N_i and maybe some other nodes from IN to $\overline{\text{IN}}$, and add the inserted links to L and remove the deleted links from L.

The step explained above is then repeated for the remaining nodes in IN. When all nodes in IN are transferred to $\overline{\text{IN}}$, we obtain a feasible solution.

Once a feasible solution is obtained, the next step is a trial process to find a new feasible configuration with lower cost. This is done by examining each link with every other link. (The question is, if the examined links are removed and we insert new links such that the feasibility

is preserved, can the cost be decreased?) If the cost resulting is lower, then the improvement is adopted.

As an example, let us consider a feasible configuration for $d_i = 2$ for all nodes as shown in Figure 6.

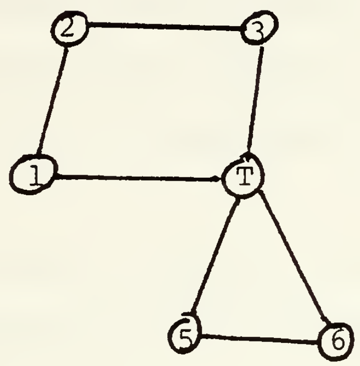


FIGURE 6. A FEASIBLE SOLUTION FOR $d_i = 2$

The set L of this solution is

$$L = \{\ell_{1T}, \ell_{12}, \ell_{23}, \ell_{3T}, \ell_{5T}, \ell_{56}, \ell_{6T}\} .$$

Suppose we examine ℓ_{1T} with respect to every other link element L . Clearly ℓ_{1T} cannot be examined with ℓ_{12} since they both have a common point at N_1 . To examine ℓ_{1T} with ℓ_{23} means to remove links ℓ_{1T} and ℓ_{23} and to insert ℓ_{13} and ℓ_{2T} . If this new configuration results in a lower cost, the configuration is adopted and the set L is updated, otherwise we examine ℓ_{1T} with the other links, for example, ℓ_{5T} by removing ℓ_{1T} and ℓ_{5T} and inserting ℓ_{15} . The link ℓ_{1T} cannot be examined with

ℓ_{56} since by removing ℓ_{1T} and ℓ_{56} , an insertion of either ℓ_{15} or ℓ_{16} will result in a nonfeasible configuration.

If any of the examinations above results in a lower cost, then the new configuration is adopted, and the step is repeated again with a new set L . The step is terminated when all links in L have been examined and no lower cost obtained.

The examination of links in the feasible solution is actually an approach to arrive eventually at a "near-optimal" configuration.

The algorithm will be written as follows:

1. Set IN = NM

   $\overline{IN} = \{0\}$

   L , the set of existing links, contains only links connecting the nodes directly to the terminals.

   Compute the cost of the configuration.

2. Pick any node $N_i \in IN$

   a) Consider inserting a link from N_i to every other node in NM . Let N_k be one of these nodes. Compute the cost if we insert link ℓ_{ik} and delete links for ℓ_{iT} , $\ell_{kT} \in L$.
   Do this for $N_k \in NM$, $k \neq i$, and pick the one having minimum cost.

b) If N_i can be transferred to $\overline{IN}$, update IN, and L and then if $IN \neq \{0\}$ go to Step 2 for a new N_i which is an element of the updated IN. If N_i cannot be transferred to $\overline{IN}$ repeat Step 2 a) with every other node in NM except N_k picked in step 2 a).

c) If $IN = \{0\}$ go to Step 3, otherwise go to Step 2.

3. Arrange the elements of L in any order. Let ℓ_{ih} be the first element of L and $\ell_{k\ell}$ be the next element to ℓ_{ih} in L.

a) If ℓ_{ih} and $\ell_{k\ell}$ have a common point at T, and if it is feasible to do so, connect the other end points if they have not been connected and delete ℓ_{ih} and $\ell_{k\ell}$. If the other end points have been connected, go back to Step 3 for the next $\ell_{k\ell}$.

If ℓ_{ih} and $\ell_{k\ell}$ have a common point at, say N_k, the examination cannot be executed, go back to Step 3 for the next $\ell_{k\ell}$.

If ℓ_{ih} and $\ell_{k\ell}$ have no common points, delete ℓ_{ih} and $\ell_{k\ell}$ and insert ℓ_{ih} and $\ell_{k\ell}$ or $\ell_{i\ell}$ and ℓ_{hk} if there are no such links and if it is feasible to do so.

For any new configuration obtained, compute the cost.

b) If the cost obtained in (a) is lower, adopt the configuration, update L and go back to Step 3 with the updated L, otherwise repeat Step 3 a) with the next $\ell_{k\ell}$.

c) If for all $\ell_{k\ell}$ no lower cost has been found, go to Step 4.

4. Repeat Step 3 for the next element to ℓ_{ih}.

5. If for all $\ell_{ik} \in L$ no improvement in cost has been found, stop the algorithm and adopt the minimum cost obtained and the configuration associated with it as the solution.

V. EXAMPLE

Let us consider the following problem. Suppose in the j^{th} cluster, the nodes are located as shown in Figure 7. It was decided to locate a satellite terminal T at N_4 .

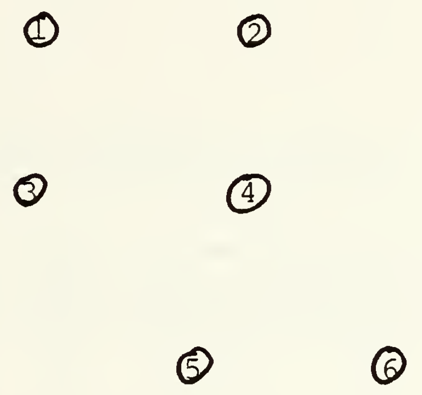


FIGURE 7. NODES LOCATION

The link redundancy for each node is $M_{iT} = 2$. Hypothetical data concerning the parameters of the network are given as follows:

The demand of each node:

$$n_1 = 3 \qquad n_3 = 3 \qquad n_5 = 4$$

$$n_2 = 4 \qquad n_4 = 5 \qquad n_6 = 3$$

Cost I_i	
Capacity	I_i
12	50
24	75
36	100

Cost G	
Capacity	G_j
24	400
48	750

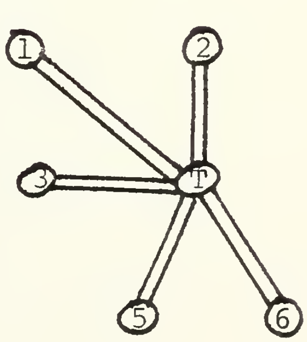
COST MATRIX $C = c_{ik}$

	1	2	3	4	5	6
1		2	3	4	7	8
2			4	3	5	4
3				1	3	5
4					1	2
5						2
6						

SOLUTION:

1. Start with initial configuration, $IN = \{N_1, N_2, N_3, N_5, N_6\}$, $\overline{IN} = \{0\}$

   The cost of this configuration is:



   $C_{1T} = 3 \times 4 = 12$; $C_{T1} = 3 \times 4 = 12$

   $C_{2T} = 4 \times 3 = 12$; $C'_{T2} = 4 \times 3 = 12$

$C_{3T} = 3 \times 1 = 3; \quad C_{T3} = 3 \times 1 = 3$

$C_{5T} = 4 \times 1 = 4; \quad C_{T5} = 4 \times 1 = 4$

$C_{6T} = 3 \times 2 = 6; \quad C_{T6} = 3 \times 2 = 6$

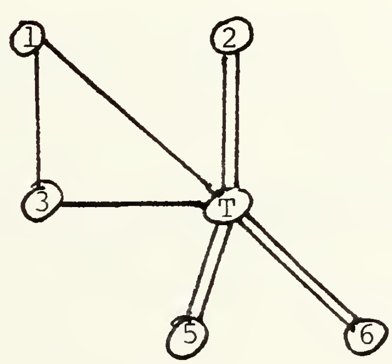
$$TC = 400 + \sum_{i=1}^{5} 50 + \sum_{i=1}^{5} C_{iT} + \sum_{i=1}^{5} C_{Ti} = 400 + 250 + 74$$

$$= 724 .$$

2. Select N_1 as the first node to be transferred to IN

   a. Consider inserting link ℓ_{1k} and deleting links ℓ_{1T} and ℓ_{kT} , k = 2,3,5,6

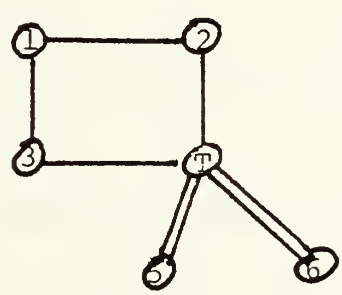
ℓ_{1k}	cost of links involving ℓ_{1k}	cost of remaining links	TC
ℓ_{12}	57	26	733
ℓ_{13}	39	44	733
ℓ_{15}	63	42	755
ℓ_{16}	60	38	748



The minimum cost is obtained if ℓ_{12} or ℓ_{13} is inserted. Let us insert ℓ_{13}, transfer N_1 and N_3 to $\overline{IN}$, and thus now $IN = \{N_2, N_5, N_6\}$ and $\overline{IN} = \{N_1, N_3\}$.

b-1 Since N_1 could be transferred, let us take an element N_2 from updated IN. We now consider inserting link ℓ_{2k} and deleting links ℓ_{2T} and ℓ_{kT}.

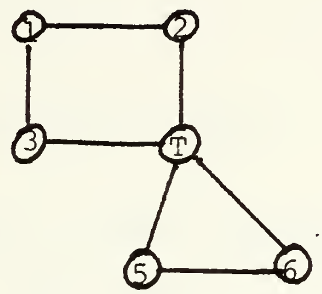
ℓ_{2k}	cost of links involving ℓ_{2k}	cost of remaining links	TC
ℓ_{21}	73	20	742
ℓ_{23}	82	20	752
ℓ_{25}	52	51	753
ℓ_{26}	51	47	748



ℓ_{21} is inserted, and we transfer N_2 to $\overline{IN}$. Now $IN = \{N_5, N_6\}$, $\overline{IN} = \{N_1, N_2, N_3\}$.

b-2 Take N_5, and consider inserting link ℓ_{5k} and deleting ℓ_{5T} and ℓ_{kT}.

ℓ_{5k}	cost of links involving ℓ_{5k}	cost of remaining links	TC
ℓ_{52}	127	12	839
ℓ_{63}	127	12	839
ℓ_{56}	29	73	752



ℓ_{56} is inserted and we transfer N_5 and N_6 to $\overline{IN}$.

c) Since $IN = \{0\}$, we arrive at a feasible configuration.

3. We write $L = \{\ell_{13}, \ell_{5T}, \ell_{12}, \ell_{2T}, \ell_{3T}, \ell_{56}, \ell_{6T}\}$ and we wish to examine ℓ_{13} and ℓ_{5T} .

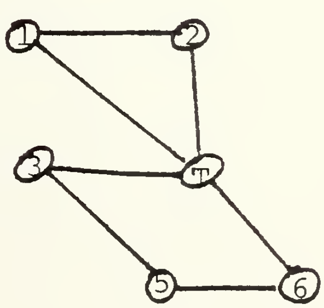
a) Since ℓ_{3T} is also an element of L , then we can only insert link ℓ_{1T} and ℓ_{53} and delete ℓ_{13} and ℓ_{57} .

The links' cost will be

$C_{12} = 4 \times 2 = 8$,

$C_{1T} = 7 \times 4 = 28$,

$C_{2T} = 7 \times 3 = 21$,



$C_{3T} = 10 \times 1 = 10$,

$C_{35} = 7 \times 3 = 21$,

$C_{56} = 7 \times 2 = 14$,

$C_{6T} = 10 \times 2 = 20$,

and

$TC = 400 + 250 + 122 = 872$.

The cost obtained is even higher than in the previous configuration. Thus the configuration considered here will not be adopted.

b) The examination of ℓ_{13} with respect to $\ell_{12}, \ell_{2T}, \ell_{56}, \ell_{6T}$ also does not result in a lower cost.

4. The examination of $\ell_{5T}, \ell_{12}, \ell_{2T}, \ell_{3T}, \ell_{56}$ and ℓ_{6T} does not result in a lower cost configuration.

5. We adopt the configuration obtained in Step 2b-2 as the solution with minimum cost of 742 .

VI. CONCLUSION

In this thesis we modeled the integration of satellite and terrestrial communication systems, without acquiring the satellite itself. The model would be different if the satellite acquisition is taken into account, and also if the optimal number of satellites must be considered. There are some studies by Yau [5] and Chou et. al [6] concerning this type of problem. Both studies were created for commercial systems, but could be modified for military purposes.

The computations involved in executing the algorithm will increase with increasing the number of nodes, but will not be excessive for problems involving no more than 10 or 20 nodes in each set R_u .

The approach used for computing the capacity of the link can be modified by considering routing only a portion of the demand of the Headquarters on each path. Thus knowing the actual demand of every Headquarters, the problem can be extended to find the best proportion of demand from each Headquarters to be routed to each path such that the construction cost of the links is minimized. Moreover, the link cost function can also be modified so that it reflects the actual condition.

In satisfying the survivability requirement, one might not use the assumptions concerning the invulnerability of

terminals and satellite links. In this case the redundancy of satellite links must also be considered, thus there will be more than one satellite terminal in each cluster. Another algorithm must be developed to solve this problem.

Finally, it is hoped that this thesis will be useful to those dealing with military communication networks. Since the solution method presented is heuristic, an improvement is still possible.

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